

NEW PROJECTS IN UNDERGROUND PHYSICS

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ABSTRACT

A large fraction of neutrino research is taking place in facilities underground. In this paper, I review the underground facilities for neutrino research. Then I discuss ideas for future reactor experiments being considered to measure θ_{13} and the UNO proton decay project.

1. Introduction

Large numbers of particle physicists first went underground in the early 1980's to search for nucleon decay. Atmospheric neutrinos were a background to those experiments, but the study of atmospheric neutrinos has spearheaded tremendous progress in our understanding of the neutrino. Since neutrino cross sections, and hence event rates are fairly small, and backgrounds from cosmic rays often need to be minimized to measure a signal, many more other neutrino experiments are found underground. This includes experiments to measure solar ν 's, atmospheric ν 's, reactor ν 's, accelerator ν 's and neutrinoless double beta decay.

In the last few years we have seen remarkable progress in understanding the neutrino. Compelling evidence for the existence of neutrino mixing and oscillations has been presented by Super-Kamiokande¹⁾ in 1998, based on the flavor ratio and zenith angle distribution of atmospheric neutrinos. That interpretation is supported by analyses of similar data²⁾ from IMB, Kamiokande, Soudan 2 and MACRO. And 2002 was a miracle year for neutrinos, with the results from SNO³⁾ and KamLAND⁴⁾ solving the long standing solar neutrino puzzle and providing evidence for neutrino oscillations using both neutrinos from the sun and neutrinos from nuclear reactors. Finally, the K2K long-baseline neutrino oscillation experiment⁵⁾ has the first indications that accelerator neutrinos also oscillate.

In preparation for this meeting, I asked the previous speaker, Sandip Pakvasa from the University of Hawaii, "What are the outstanding issues in the neutrino sector for future experiments to address?" His list was:

1. See the dip in atmospheric ν L/E distribution
2. Measure the whole solar ν energy spectrum.
3. Determine the value of Ue3 (θ_{13}).

4. Are CP violation effects large?
5. If so, what is the CP phase δ ?
6. Can we see the τ 's in $\nu_\mu \rightarrow \nu_\tau$ oscillation?
7. Can we settle the LSND question?
8. What are the absolute ν masses?
9. Is the neutrino Majorana or Dirac?
10. Is the mass hierarchy normal or inverse?
11. Are there astrophysical sources of $>\text{TeV}$ ν s?

Indeed, those questions are just the ones that have motivated neutrino physicists, and there are a plethora of new proposals for future projects at underground laboratories and accelerators. These include the study of solar, atmospheric, reactor, accelerator and astrophysical sources of neutrinos. There is also the direct search for neutrino mass in Tritium beta decay, and the search for Majorana masses in neutrinoless double beta decay.

In this paper I will review some underground projects focusing on those not found elsewhere on the agenda. I will start by discussing major existing and proposed facilities where underground physics research takes place. In Sections 3 and 4 I will briefly comment on plans for new real time solar neutrino experiments and site issues for future off-axis long-baseline neutrino experiments to measure θ_{13} .⁶⁾ In Section 5 I will present my thoughts about new reactor neutrino experiments to measure θ_{13} . In Section 6 I will return to nucleon decay and describe the UNO experiment.

2. Underground Laboratories for Neutrino Research

The nicest facility for underground physics is located at the Gran Sasso Laboratory in a mountain road tunnel in Italy. It is operated there by INFN for experimentalists from throughout the world. There are three large halls in which a number of neutrino experiments have operated and are being built. These include the Gallex and GNO experiments which have measured the pp solar neutrinos; the MACRO experiment which measured the angular distribution of atmospheric neutrinos; Borexino which is being built to measure the solar neutrinos from ${}^7\text{Be}$; the Heidelberg-Moscow neutrinoless $\beta\beta$ decay experiment on Germanium, which is the most sensitive search to date; the LVD detector which is searching for neutrinos from supernovae; and the OPERA and ICARUS projects which will measure neutrinos associated with the CERN Neutrinos to the Gran Sasso (CNGS) program starting in 2006.

The Kamioka mine is located in the Japanese Alps on the western side of Japan. It is home to the 50 kiloton Super-Kamiokande water Cerenkov detector. In November

2002 it started running again, with half the photo-tube coverage that it had before its accident in December 2001. Nearby is the KamLAND detector which looks at reactor neutrino disappearance from 26 reactors throughout Japan. There are also early plans to put the one megaton Hyper-Kamiokande experiment in a cavern in the Tochibora mine, about 3 km south of the present Mozumi mine. That could pair with the present Super-Kamiokande facility as an off-axis site from the new JPARC accelerator at Tokai.

The Baksan facility is located in the Caucasus mountains in southern Russia. The Gallium solar ν experiment SAGE is located in a deep section with a minimum overburden 4700 MWE. The Gallium experiment was crucial in confirming the solar neutrino deficit. Also located at Baksan is the 4 layer Baksan Underground Scintillation Telescope (BUST) located at an minimum overburden of 850 MWE. BUST has been studying the zenith angle distribution of upward atmospheric induced neutrino events, which is relevant to the atmospheric neutrino deficit.

The Sudbury Neutrino Observatory (SNO) is taking data that has provided revolutionary insight into the properties of neutrinos and the core of the sun. The detector is in INCO's Creighton mine near Sudbury, Ontario. SNO uses 1000 tons of heavy water, on loan from Atomic Energy of Canada Limited (AECL), contained in a 12 meter diameter acrylic vessel. Neutrinos which react with the heavy water (D₂O) are detected by an array of 9600 photomultiplier tubes. The detector laboratory is extremely clean to reduce background signals from radioactive elements. Besides the heavy water detector, the Canadian government has recently funded a new international facility for underground science called SNOLAB which will provide a low background facility nearby.

The Soudan Underground Physics Laboratory is located in a facility maintained by the State of Minnesota Department of Natural Resources and operated as a tourist attraction as part of northern Minnesota's iron range. Two connected laboratory spaces are located on the 27th level with an overburden of 2100 MWE. The nucleon decay experiment Soudan 2⁷⁾ operated in one hall from 1986-2001. Also in that hall the Cryogenic Dark Matter Search (CDMS) is being installed. The 5.6 kton MINOS iron toroid detector which will serve as the far detector for the Fermilab long-baseline neutrino experiment is 96% installed as of May 2003.

The Frejus laboratory is in a tunnel between France and Italy. It was also the site of a proton decay experiment which ran from 1984-1990. The construction of a parallel safety tunnel has been motivated by the 2000 accident in the Mont Blanc tunnel. That provides the opportunity for considering construction of a large new scientific laboratory space that could be used for a large new detector such as UNO. Such a detector, 190 km from CERN, would be useful in conjunction with a new neutrino superbeam from CERN using the proposed Superconducting Proton LINAC (SPL) or a beta beam using the SPL injecting ⁶He or ¹⁸Ne from ISOLDE into the SPS and a new storage ring.⁸⁾

The Waste Isolation Pilot Plant, or WIPP facility, in Carlsbad New Mexico was built to store low-level radioactive waste from the US military. It is the world's first underground repository licensed to safely and permanently dispose of transuranic radioactive waste left from the research and production of nuclear weapons. After more than 20 years of scientific study, public input, and regulatory struggles, WIPP began operations on March 26, 1999. It is considered as a possible site for the supernova experiment OMNIS which will feature a measurement of the neutral current events from supernovae; the 400 kiloton proton decay experiment UNO; and EXO, a new neutrino-less $\beta\beta$ decay experiment which uses Xenon. Experimental facilities located in the salt are sufficiently removed from the radioactive waste that they present no backgrounds to any of these experiments.

There is considerable interest in the United States in developing a National Underground Laboratory Facility (NUSEL) for future neutrino experiments. A panel was appointed in 2002 by the U.S. National Research Council to study future neutrino facilities, with an emphasis on NUSEL and also a neutrino telescope ICE-CUBE. In its conclusion section, they wrote⁹⁾: "In summary, our assessment is that a deep underground laboratory in the US. can house a new generation of experiments that will advance our understanding of the fundamental properties of neutrinos and the forces that govern the elementary particles, as well as shedding light on the nature of the dark matter that holds the Universe together. Recent discoveries about neutrinos, as well as new ideas and technologies make possible a broad and rich experimental program. Considering the commitment of the U.S. community and the existing scientific leadership in this field, the time is ripe to build such a unique facility." The favored location for NUSEL is the Homestake South Dakota mine where the famous Davis experiment ran for many years. There is also a proposal to locate the laboratory with horizontal access in a new facility near San Jacinto California.

India was home to one of the earliest and deepest underground facilities with the KGF mine and experiment from the 60's through the early 90's. Now a group from several institutes throughout India is studying the possibility of a new neutrino observatory to measure atmospheric neutrinos and be the possible site for a long-baseline neutrino program from a neutrino factory. Two sites which have hydro-electric projects near large hills are being considered. The PUSHEP site (Pykara Ultimate Stage Hydro Electric Project) near Ooty in Tamil Nadu is located in a vein of high quality rock, and is also close to a high altitude cosmic ray facility. The RAMMAM Hydro Electric Project site is located in the Himalayas near Darjeeling, and has the possibility of a laboratory with a much greater overburden, suitable for solar neutrino experiments. A project team has gotten a grant to study both sites

and design a 30 kiloton Iron/RPC calorimeter for atmospheric neutrinos.

3. Real Time Solar Neutrino Experiments

Ray Davis, a winner of the 2002 Nobel prize in physics, started underground physics in the 1960's with his Homestake solar neutrino experiment. Solar neutrino experiments have the most stringent background requirements to date which has generally made those experiments the deepest, and driven the depth requirements for consideration of a multi-purpose underground laboratory.

Previous solar neutrino experiments have involved chemical extraction of chlorine or gallium. The next solar neutrino experiments will be Borexino and KamLAND,¹⁰⁾ which will measure solar neutrino experiments in real time.

Ideas for future real-time solar neutrino experiments are listed in Table 1.

Experiment ¹¹⁾	Status	Feature
Borexino	under construction	scintillator
KamLAND	running	scintillator
HELLAZ	R&D	Liquid Helium
XMASS	R&D	Liquid Xenon
CLEAN	R&D	Liquid Neon
HERON	R&D	cryogenic
LENS	R&D	¹⁷⁶ Yb
MOON	R&D	¹⁰⁰ Mo
GENIUS	R&D	νe in Germanium

Table 1: Possible Future Real Time Solar Neutrino Experiments

4. Can Off-axis Experiments be at the Surface?

The long-baseline programs that are or soon will be running are in Japan (K2K), Europe (CNGS) and the United States (NuMI/MINOS). The far detectors for all three projects are located deep enough underground that there are negligible cosmic rays mimicking beam induced neutrino interactions. There was a previous proposal at Brookhaven¹⁴⁾ for a long-baseline neutrino experiment on the surface using a water Cerenkov Detector. In their proposal, they performed the only study of long-baseline neutrino backgrounds in the relevant energy region of which I'm aware.

A new long-baseline experiment is being proposed that would use a 50 kton detector to search for $\nu_\mu \rightarrow \nu_e$ in the NuMI beam¹²⁾ as evidence for a non-zero value of θ_{13} . The beam spill with one-turn extraction from the Fermilab Main Injector will be $10\mu s$ long. Each year, assuming 2×10^7 pulses and an area of about 1000 m^2 , there will be 1.2×10^7 muons and 8×10^5 neutrons ($E > 0.1 \text{ GeV}$) going through a detector on the surface. There are four possible handles to reduce these backgrounds:

1. overburden
2. active veto
3. pattern recognition
4. bunch timing

The last option would drive up the cost of electronics and cannot reduce the time window substantially. Of course most muons do not look like contained events, but the existence of cracks or other dead regions in the detector will make muons a problem. BNL889 had qualitatively different pattern recognition issues than the FNAL off-axis experiment will experience, but it was going to be a homogeneous detector without cracks. I scale and compare the backgrounds for illustrative purposes only. NuMI off-axis will need a rejection of 2.1×10^6 for μ 's and 1.6×10^5 for neutrons, to obtain Signal/Background > 1 for $\sin^2 2\theta_{13} = 0.01$. BNL P889 calculated that they would achieve a rejection of 7×10^5 for μ 's and 3.4×10^2 for neutrons using an active veto and pattern recognition for electrons 0.3 to 4 GeV. I conclude that operating NuMI-off-axis on the surface without overburden will be challenging.

5. Reactor Experiments

From the discovery of the neutrinos by Reines and Cowan¹⁵⁾ at Savannah River to the evidence for $\bar{\nu}_e$ disappearance at KamLAND⁴⁾, reactor neutrino experiments have studied neutrinos in the same way – observation of inverse beta decay with scintillator detectors. Since the signal from a reactor falls with distance L as $1/L^2$, as detectors have moved further away from the reactors over the years, it has become more important to reduce backgrounds. That can be done by putting experiments underground; and experiments one kilometer or more away from reactors (Chooz, Palo Verde and KamLAND) have been underground.

The KamLAND experiment measured a 40% disappearance of $\bar{\nu}_e$ presumably associated with the 2nd term in Equation 1:

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \cong -\sin^2 2\theta_{13} \sin^2(\Delta m_{atm}^2 L/4E) - \cos^4 \theta_{13} \sin^2 2\theta_{12} \sin^2(\Delta m_{12}^2 L/4E) + 1 \quad (1)$$

The Chooz and Palo Verde data put a limit on θ_{13} (through the first term in Equation 1) of $\sin^2 2\theta_{13} < 0.1$. Those experiments could not have had greatly improved sensitivity to θ_{13} because of uncertainties related to knowledge of the flux of neutrinos from the reactors. They were designed to test whether the atmospheric neutrino anomaly might have been due to $\nu_\mu \rightarrow \nu_e$ oscillations, and hence were searching for large mixing.

Any new experiment to look for non-zero values of θ_{13} would need the following properties:

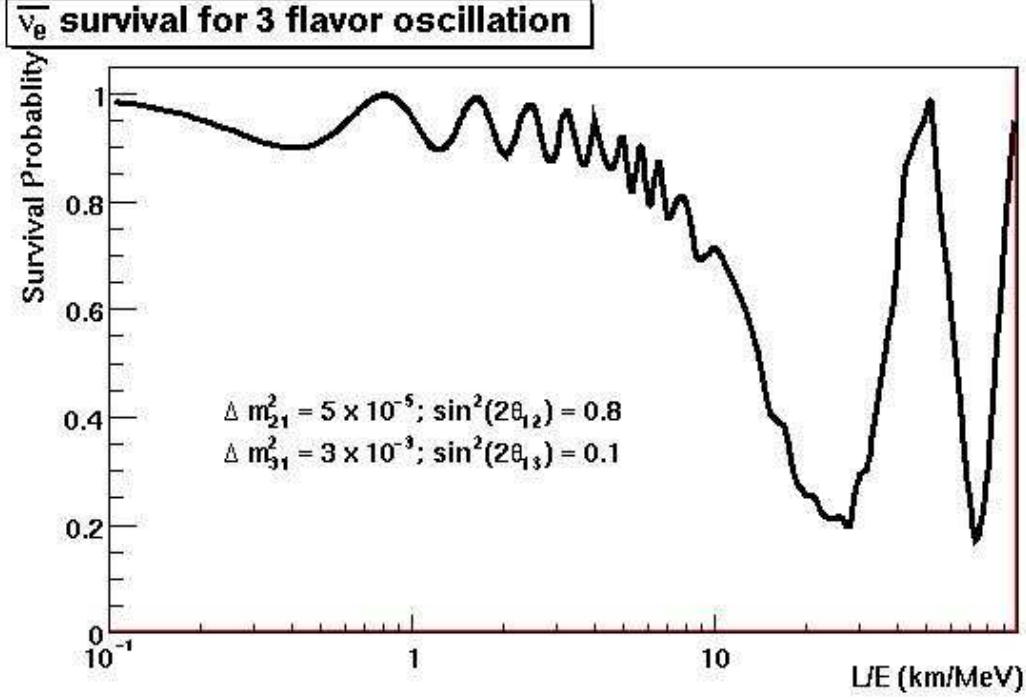


Figure 1: Probability of ν_e disappearance versus L/E for θ_{13} at its current upper limit

- two or more detectors to reduce uncertainties to the reactor flux
- identical detectors to reduce systematic errors related to detector acceptance
- carefully controlled energy calibration
- low backgrounds and/or reactor-off data

In Equation 1, the values of θ_{12} , Δm_{12}^2 and Δm_{atmo}^2 are approximately known. In Figure 1, The probability of $\bar{\nu}_e$ disappearance as a function of L/E is plotted with θ_{13} assumed to be at its maximum allowed value. Note that CP violation does not affect a disappearance experiment, and that matter effects can be safely ignored in a reactor experiment. The large variation in P for $L/E > 10$ km/MeV is the effect seen by KamLAND and solar ν experiments. The much smaller deviations from unity for $L/E < 1$ km/MeV are the goal for an accurate new reactor experiment.

The optimization of detector distances for such a new experiment is straightforward. The statistical power comes from measuring a deficit of $\bar{\nu}_e$ (up to a few percent) at the far detector, along with a change in the energy spectrum consistent with that deficit. Up to systematic errors in the rate and energy spectrum, one can construct a χ^2 difference between a near detector and a far detector. In Figure 2, the detector

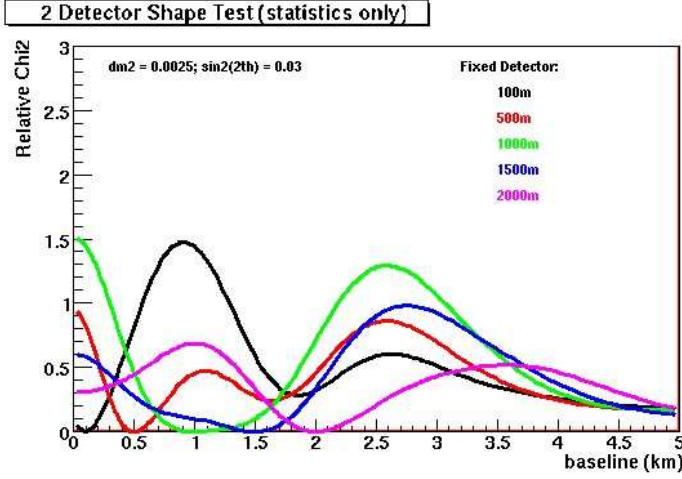


Figure 2: $\Delta\chi^2$ for two detectors versus detector location for statistics only. Other oscillation parameters have been fixed. Locations at 100 m and 1000 m are preferred.

location has been fixed for each curve and the statistical power of these tests calculated as the location of the second detector is varied. In Figure 3, one detector has been fixed at 1000 m while the location of the second detector is varied with a 1% systematic error folded in. The different curves in that plot reflect uncertainty in the parameter Δm_{atm}^2 . The optimum locations for detectors is thus sensitive to eventual systematic errors as well as oscillation parameters. But a near detector around 100m and a far detector around 1000 m will be near the optimum. Since the civil construction of laboratories might contribute half or more to the cost of an experiment, finding existing labs at those locations may change the optimization.

A list of possible sites for a new reactor experiment is included in Table 2, along with a tabulation of previous reactor experiment sites. Two specific proposals have been made. The KR2DET¹⁶⁾ experiment would use the Krasnoyarsk reactor in Russia, and two detectors located at 115 and 1000 m. That site has two attractive features: 1) There is an entire city built at 600 MWE depth with possible locations for the detector sites, and 2) The fuel cycle for that reactor is better understood than for most reactors because the fuel is changed every few months rather than years. The other specific idea is the Kashiwazaki¹⁷⁾ site in Japan, the location of 7 reactors. It is the most powerful reactor complex in the world, 24 Gw. The reactors come in one cluster of 4 and one cluster of 3, so there would need to be two near detectors and one far detector, possibly located in shafts created by a large drill. Other sites in the United States, France, Taiwan and Brazil are being considered. The site in Taiwan may be interesting because of an existing road tunnel 2 km from the reactor.¹⁸⁾

A sensitivity of 0.02 in $\sin^2 2\theta_{13}$ can be achieved with as little as 250 ton-Gigawatt-

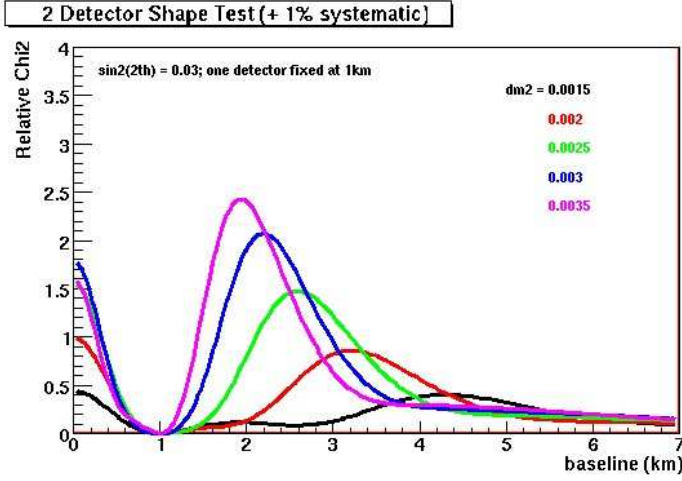


Figure 3: $\Delta\chi^2$ for two detectors with one detector fixed at 1000m and the other location varied. A 1% bin-to-bin systematic error is included, but the Δm_{atm}^2 has been allowed to vary from 1.5 to $3.5 \times 10^{-3} \text{ eV}^2$

years, while an exposure of 8000 ton-Gigawatt-years may be required to achieve a sensitivity of 0.01.¹³⁾ A two or more detector reactor experiment seems to be an attractive option as part of the search for θ_{13} . It can probably find a non-zero value for θ_{13} faster and less expensively than an off-axis experiment. It does not face the degeneracies regarding CP parameters and the sign of Δm^2 , and hence cannot address those issues. But a measurement of θ_{13} by reactors followed by optimized off-axis experiments would together measure neutrino parameters with much less uncertainty due to degeneracies and correlations.

6. UNO

One of the reasons for the tremendous progress in understanding the neutrino has been the fact that several detectors were built underground to search for nucleon decay. They haven't found nucleon decay, but have made a number of other discoveries. Perhaps the lesson is that we should build yet another detector to look for nucleon decay. And maybe we will find that the nucleon decays!

The UNO detector¹⁹⁾ is proposed as a next generation underground water Cerenkov detector that probes nucleon decay beyond the sensitivities of the highly successful Super-Kamiokande (Super-K) detector utilizing a well-tested technology. [1] The baseline conceptual design of the detector calls for a "Multi-Cubical" design with outer dimensions of 60x60x180 m³. The detector has three optically independent cubical compartments with corresponding photo-cathode coverage of 10%, 40%, and 10%, respectively. The total (fiducial) mass of the detector is 650 (440) kton, which is about 13 (20) times larger than the Super-K detector. The discovery potential

Reactor	Location	L	Power	Overburden	Detector Mass
Chooz	France	1100 m	8.5 Gw	300 MWE	5 ton
Bugey	France	49/95	5.6	16	1/0.5
Palo Verde	Arizona	890	11.6	32	11.3
KamLAND	Japan	< 180 >	200 (26)	2700	1000
Krasnoyarsk	Russia	115/1000	1	600	46
Diablo Canon	California	~ 1	6.1	600	
Wolf Creek	Kansas	~ 1	3.2		
Boulby	UK	25	3.1	2860	
Heilbronn	Germany	19.5	6.4	480	
Kashiwazaki	Japan	1.7	24.3		20 ton
Texono	Taiwan	2.0	4.1		
Angra	Brazil		4.0		
IMB	Ohio	10	1.2	1570	

Table 2: Past Reactor Sites and Future Possibilities

of the UNO detector is multi-fold. The probability of UNO discovering proton decay via vector boson mediated $e^+\pi^0$ mode is predicted to be quite high ($\sim 50\%$) in modern Grand Unification Theories (GUTs). Water Cerenkov technology is the only realistic detector technology available today to allow a search for this decay mode for proton lifetimes up to 10^{35} years. If the current super-symmetric GUT predictions are correct, UNO can discover proton decay via νK^+ mode. The important design issue for any nucleon decay detector is to keep backgrounds low while maintaining high efficiency. UNO is able to take advantage of the understandings about these two modes that have come from extensive analysis in the Super-Kamiokande experiment. Modeling the backgrounds and efficiencies in an UNO sized detector, the sensitivity for these two modes is plotted versus exposure in Figure . While further advances are possible, it is seen that substantial increase in proton decay sensitivity would be achieved.

In addition to nucleon decay, UNO will be sensitive to a large variety of other interesting topics. UNO will be able to detect neutrinos from supernova explosions as far away as the Andromeda galaxy. In case of a galactic supernova explosion, UNO will collect $\sim 100k$ neutrino events from which the millisecond neutrino flux timing structure can be extracted. This could provide us with an observation of black hole formation in real-time as well as a wealth of information to precisely determine the core collapse mechanism. Discovery of supernova relic neutrinos (SRN) is within the reach of UNO. SRN could very well be the next astrophysical neutrinos to be discovered. The predicted values of the SRN flux by various theoretical models are only up to six times smaller than the current Super-K limit. Some models have been already excluded. With much larger fiducial mass and lower cosmogenic spallation

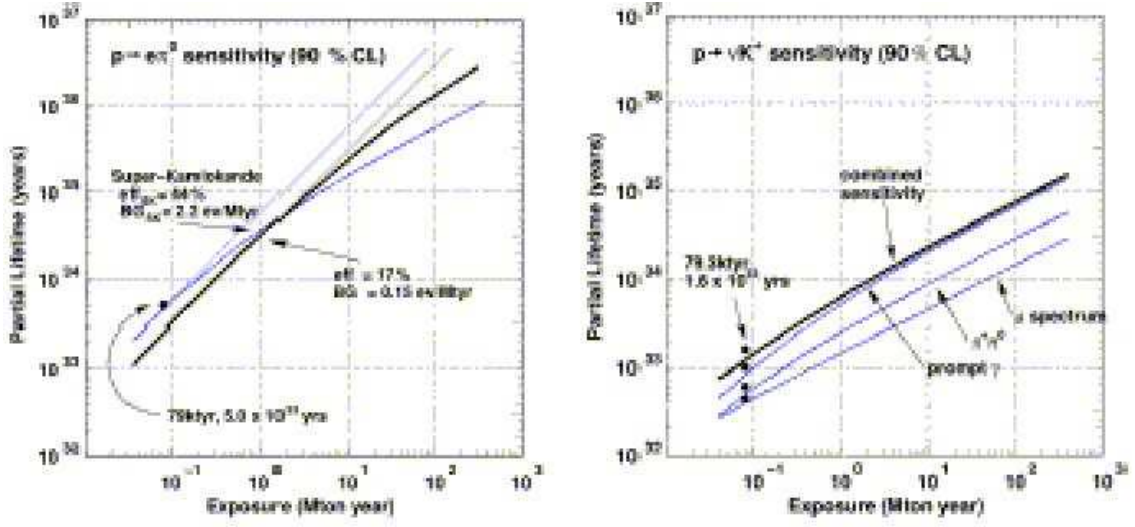


Figure 4: Sensitivity versus exposure for UNO in the modes $p \rightarrow \nu K^+$ and $p \rightarrow e\pi^0$.

background, UNO situated at a depth 4000 MWE can cover all of the predicted flux range. UNO is an ideal distant detector for a long-baseline neutrino oscillation experiment with neutrino beam energies below about 10 GeV providing a synergy between the accelerator and the non-accelerator physics. UNO provides other opportunities, such as the ability to observe oscillatory behavior and appearance in the atmospheric neutrinos; precision measurement of temporal changes in the solar neutrino fluxes; and searches for astrophysical point sources of neutrinos and dark matter in an energy range difficult for larger, more coarse-grained undersea and under-ice detectors to cover.

7. Summary

There is a tremendous diversity of future neutrino projects and a number of interesting measurements to be made, almost all of them involving detectors located at facilities underground. Even with the tremendous progress we have already seen in the neutrino field, we are well on our way to answering the questions that were posed in Section 1.

8. Acknowledgments

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